

## A 2.4–80 $\mu\text{m}$ spectrophotometric study of SS 433 with ISO

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**Abstract.** We present ISOPHOT spectrophotometric observations of SS 433 at four different orbital phases in 1996 and 1997. The HeI + HeII lines in both spectra of SS 433 and the Wolf-Rayet star WR 147, a WN8+BO5 binary system, closely match. The 2.5–12  $\mu\text{m}$  continuum radiation is due to an expanding wind free-free emission in an intermediate case between optically thick and optically thin regime. A rough mass loss rate evaluation gives about  $\sim 1.4 \times 10^{-4} \text{ M}_{\odot} \cdot \text{yr}^{-1}$ . Results are consistent with a Wolf-Rayet-like companion to the compact object in SS 433.

### 1. Introduction: SS 433 optical and near-infrared stationary spectra

The X-ray binary source SS 433 and its relativistic jets have been studied at many wavelengths, with yet no consensus about the component masses and the evolutionary status of the system (see Margon 1984 for a review). As shown by van den Heuvel, Ostriker, & Petterson (1980) the optical stationary spectrum and photometric characteristics of SS 433 are consistent with those of an Of or Wolf-Rayet (WR)-like star with an extremely large rate of stellar wind mass loss. The predicted mass transfer rates are much larger than the likely mass loss rates in the precessing jets (Begelman et al. 1980). King, Taam, & Begelman (2000) argue that most of the transferred mass is lost from the accretion flow at large radii and is presumably the source of the stationary H $\alpha$  line and the associated free-free continuum in the near-infrared seen by Giles et al. (1979).

We present middle and far-infrared spectrophotometric observations of SS 433 with ISOPHOT (Kessler et al. 1996; Lemke et al. 1996) to test this interpretation. We will discuss the spectral shape of the continuum and compare the emission lines in SS 433 and the binary Wolf-Rayet star WR 147.

### 2. Observations

#### 2.1. Spectrometry and photometry with ISOPHOT (2.4–80 $\mu\text{m}$ )

We took ISOPHOT archived data on SS 433 which was observed by ISO on 1996 November 3; 1997 April 11, 17, 23 each time during 2156 s total; the binary orbital phases were respectively 0.11, 0.27, 0.71, 0.16 with uncertainty

0.19 according to the ephemeris of Kemp et al. (1986) (phase 0 corresponds to the eclipse of the accretion disk by the normal star) ; the precession phases were respectively 0.84, 0.81, 0.85, 0.89 (phase 0 when the approaching jet lies farthest to the line of sight). The observing modes were ISOPHOT-S spectrophotometry in the ranges 2.4–4.8 and 6–12  $\mu\text{m}$  with spectral resolutions  $\sim 0.04$  and  $0.1 \mu\text{m}$  respectively, and ISOPHOT multi-filter photometry at 12, 25, 60  $\mu\text{m}$ . The four 2.4–12  $\mu\text{m}$  SS 433 spectra are shown in Fig. 1a; they are de-reddened according to Lutz et al. (1996) assuming  $A_V = 8$  (Margon 1984).

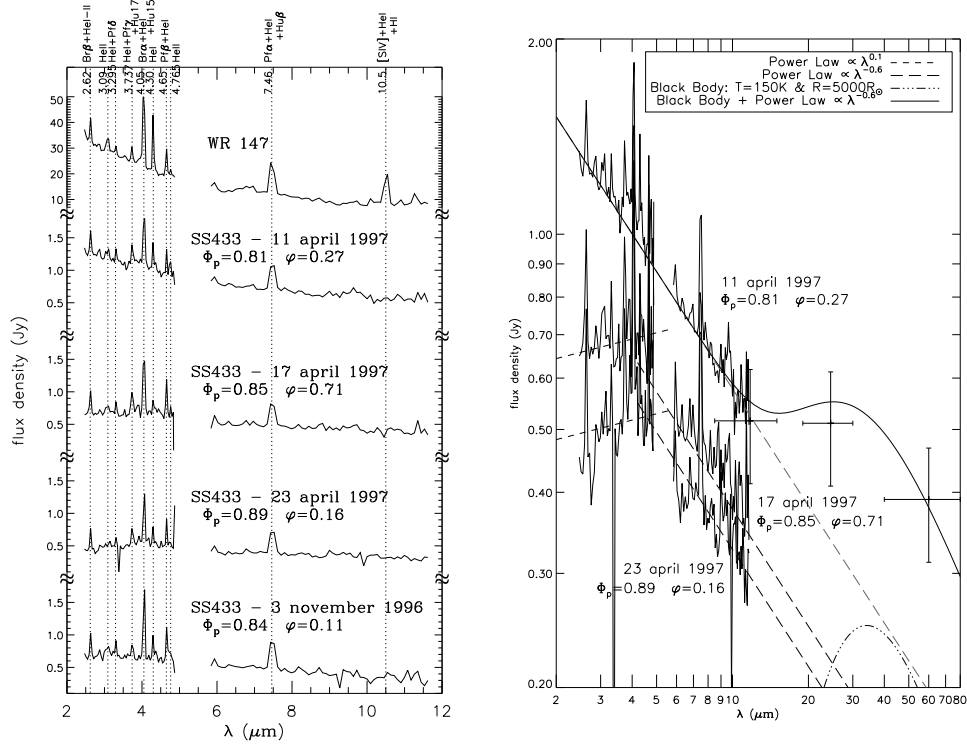


Figure 1. a (left): comparison between WR147 and SS 433 spectra.  
b (right): simple modeling of April 1997 SS 433 spectra (see text).

## 2.2. Comparison with the WR 147 spectrum

Several Wolf-Rayet stars were observed with the high spectral resolution Short Wavelength Spectrometer (SWS) on ISO, which archival data were smoothed to the lower resolution of ISOPHOT-S and compared to SS 433 spectra. The lines detected in these latter spectra closely match the spectrum of the Wolf-Rayet WR 147, a WN8+B05 binary system (see Fig. 1a), except for the 10.5  $\mu\text{m}$  [SIV]+HeI+HI line missing in SS 433. The main detected lines, as at 2.62, 4.05, 4.30 and 7.46  $\mu\text{m}$  are identified according to Morris et al. (2000).

## 3. Interpretation

### 3.1. Spectral fitting of the mid-infrared continuum flux of SS 433

Fitting of the continuum flux of SS 433 on 1997 April 11, 17, 23, is shown on Fig. 1b (the 1996 spectrum is very similar to the 17 April 1997 one). In the

4–12  $\mu\text{m}$  range, the slope ( $\alpha$  with  $F_\nu \sim \nu^\alpha$ ) is in excellent agreement with the 0.6 value expected from the free-free emission of an extended optically thick envelope possibly far from spherical (Schmid-Burgk 1982); between 2.4 and 4  $\mu\text{m}$  on 17 and 23 April, the slope becomes flatter  $\alpha \simeq -0.1$  as going to optically thin free-free emission; above 12  $\mu\text{m}$ , observed only with broad-band filters on April 11, a black-body from dust at  $T = 150 \text{ K}$  ( $R = 5000 R_\odot$ ) has been added to the optically thick free-free emission, although this far-infrared emission is also consistent with optically thin dust at 120–250 K.

### 3.2. Rough mass loss rate evaluation

As Ogley, Bell-Burnell, & Fender (2001) for Cyg X-3, we evaluated the mass loss rate of this free-free emitting wind in SS 433, following the Wright & Barlow (1975) formula (8). With a distance  $D = 3.2 \text{ kpc}$ , a Gaunt factor  $g \sim 1$ , a  $F_\nu = 1000 \text{ mJy}$  flux at 4  $\mu\text{m}$  ( $7.5 \times 10^{13} \text{ Hz}$ ), and for a WN-type wind (where the mean atomic weight per nucleon  $\mu = 1.5$ , the number of free electrons per nucleon  $\gamma_e = 1$  and the mean ionic charge  $Z = 1$ ) with a velocity of  $v_\infty = 1500 \text{ km.s}^{-1}$ , we find :  $\dot{M} = 1.4 \times 10^{-4} M_\odot.\text{yr}^{-1}$ . This is in good agreement with the mass transfer rate estimated by van den Heuvel et al. (1980) assuming a normal homogeneous WR wind, or with recent mass transfer values obtained from simulations of SS 433 evolution by King et al. (2000). However, this result is higher than the recent revised WN mass-loss rate estimates, which have been lowered by a factor 2 or 3 due to clumping in the wind (Morris et al. 1999).

### 3.3. Radio to optical spectrum of SS 433

Radio to optical continuum spectrum of SS 433, with data taken at very different epochs, is shown on Fig. 2 where the source variability is clearly seen. Note that the lower fluxes at 1.6 and 5 GHz of Paragi et al. (1999) measured with the VLBA + VLA are explained by the highest angular resolution spectral mapping of the inner core and jets of the binary system. The near-infrared and optical wavelengths slopes are steeper ( $\alpha \sim 1-3$ ) than the one observed in mid-infrared with our ISOPHOT spectra. Giles et al. (1979) and McAlary & McLaren (1980) interpreted these B to K band filter fluxes as the addition of a hot black body (a 15 700 K star or the accretion disk ?) and an optically thin free-free emission.

## 4. Conclusions

We have shown that the mid-infrared continuum of SS 433 between 2.5 - 12  $\mu\text{m}$  can be explained by the free-free emission of an expanding wind in the intermediate case between optically thick and optically thin regime. This result is consistent with the assumed large mass expelled from the super-Eddington accretion disk at large radii (King et al. 2000), and with the wind-like equatorial outflow observed by Paragi et al. (1999) - and their origin is probably a stellar wind from the companion star. The close match between the HeI + HeII emission lines detected in SS 433 and WR 147 is consistent with a Wolf-Rayet-like companion to the compact object. Thus SS 433 might be the second known X-ray binary containing a Wolf-Rayet star with a compact object after the galactic relativistic jet source Cygnus X-3 (Hanson, Still, & Fender 2000 and references therein).

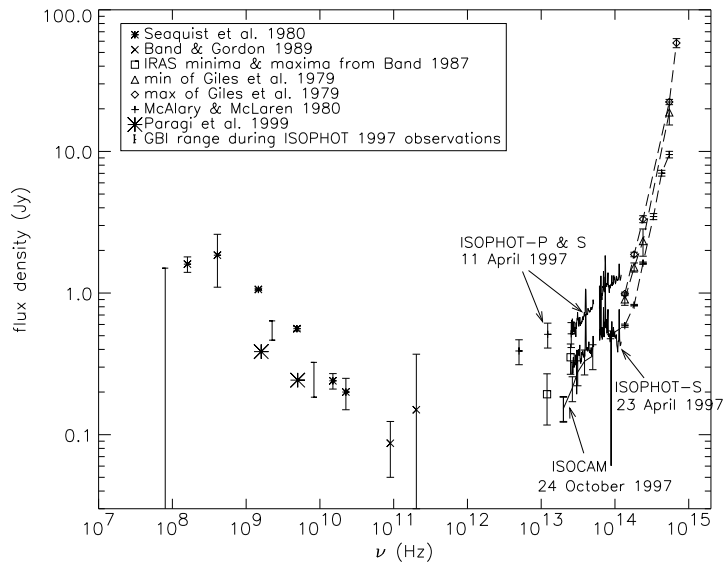


Figure 2. Radio to optical spectrum of SS 433

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